Sheet-Type Braille Displays by Integrating Organic Field-Effect Transistors and Polymeric Actuators

Yusaku Kato, *Student Member, IEEE*, Tsuyoshi Sekitani, Makoto Takamiya, *Member, IEEE*, Masao Doi, Kinji Asaka, Takayasu Sakurai, *Fellow, IEEE*, and Takao Someya, *Member, IEEE*

***Abstract*—A large-area, flexible, and lightweight sheet-type Braille display has been successfully fabricated on a plastic film by integrating high-quality organic transistors and soft actuators. An array of rectangular plastic actuators is mechanically processed from a perfluorinated polymer electrolyte membrane. A small semisphere, which projects upward from the rubberlike surface of the display, is attached to the tip of each rectangular actuator. The effective display size is 4×4 cm^2. Each Braille letter consists of 3×2 dots and 24 letters; in other words, 6 letters $\times$ 4 lines can be displayed. Pentacene field-effect transistors with top-contact geometry have a channel length of 20 μm and a mobility of 1 cm^2/V $\cdot$ s. The Braille dots on one line are driven for 0.9 s. The total thickness and weight of the entire device are 1 mm and 5.3 g, respectively. The present scheme will enable people with visual impairments to carry the Braille sheet display in their pockets and read Braille e-books at any time. Since all the device components are manufactured on plastic films, these sheet-type Braille displays are mechanically flexible, lightweight, shock resistant, and potentially inexpensive to manufacture; therefore, they are suitable for mobile electronics.**

***Index Terms*—Braille display, large-area electronics, organic transistor, polymer actuator, tactile display.**

I. Introduction

An ORGANIC field-effect transistor (FET) [1]–[12] belongs to a new class of electronics that can be fabricated directly on plastic films at ambient temperatures; therefore, it is mechanically flexible, lightweight, very thin, shock resistant, and easy to transport. It is potentially inexpensive since it can be manufactured by low-cost processes using printing machines. These attributes of organic transistors cannot be achieved easily by the present silicon-based electronic materials.

Recent studies of organic transistors are driven by two major applications. The first includes flexible displays such as paperlike displays or e-paper [1], [2]. The second includes radio-frequency identification (RFID) tags [3], [4]. Since organic transistors can be manufactured by printing technologies [5], [6], they should facilitate the implementation of RFID tags on packages.

Flexible large-area sensors are recently developed applications of organic transistors. The earliest example of an organic transistor-based large-area sensor is a pressure sensor matrix. Organic transistor active matrices are used to readout pressure data from sensors. The new pressure sensor could be ideal for electronic artificial-skin applications in the future generations of robots [7], [8]. Another new development is a flexible, large-area, and sheet-type image scanner; it comprises a two-dimensional array of organic photodetectors coupled with an organic transistor active matrix for data readout [9].

Organic transistors are also suitable for large-area actuators. We have recently fabricated a prototype of a flexible, shock-resistant, and lightweight sheet-type Braille display on a plastic film by integrating high-quality organic FETs with soft actuators; this display was presented at the IEEE International Electron Device Meeting [10]. In this paper, we present a detailed technical report on this new device. An array of rectangular plastic actuators is processed from a perfluorinated polymer electrolyte membrane. A small semisphere, which projects upward from the rubberlike surface of the display, is attached to the tip of each rectangular actuator. The effective display size is 4×4 cm^2. Each letter consists of 3×2 Braille dots, and the total number of dots is 144; thus, 24 letters or 6 letters $\times$ 4 lines can be displayed. Pentacene transistors with top-contact geometry have a channel length of 20 μm and a mobility of 1 cm^2/V $\cdot$ s. The Braille dots on one line are driven for 0.9 s. The total thickness and weight of the entire device are 1 mm and 5.3 g, respectively. The present scheme will enable people with visual impairments to carry the Braille sheet display in their pockets and read Braille e-books at any time.

II. Manufacturing Process

A. Device Structure and Principles

The Braille sheet displays are manufactured by laminating three layers: the organic transistor sheet, the polymeric actuator sheet, and the cover layer. Since all the materials except the metal electrodes are made of soft materials, the entire system is thin, lightweight, and mechanically flexible (Fig. 1). A picture of a Braille sheet display in plan view is shown in Fig. 1(b). Some sections of the layers have been intentionally removed in order to reveal the internal three-layer structure, although the sizes of all three layers are identical. Fig. 1(c) shows a circuit diagram of the Braille display.

Manuscript received February 7, 2006. This work was supported in part by JST/CREST, TOKUTEI (15073204), and IT program, MEXT. Y. Kato also thanks JSPS Research Fellowships for their financial support. The review of this paper was arranged by Editor J. Kanicki.

Y. Kato, T. Sekitani, and T. Someya are with the Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan (e-mail: someya@ap.t.u-tokyo.ac.jp).

M. Takamiya and T. Sakurai are with the Center for Collaborative Research, The University of Tokyo, Tokyo 153-8904, Japan.

M. Doi is with the Department of Applied Physics, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan.

K. Asaka is with the National Institute of Advanced Industrial Science and Technology (AIST), Osaka 563-8577, Japan.

Digital Object Identifier 10.1109/TED.2006.888678

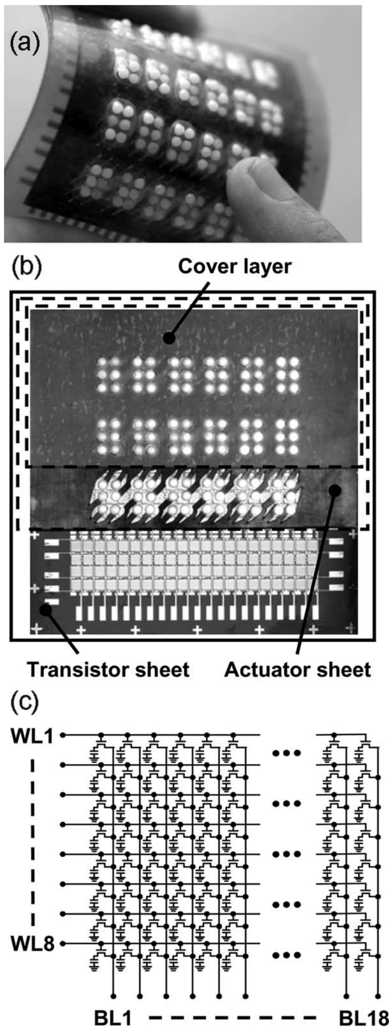

Fig. 1. Images of a Braille sheet display. (a) Image of the Braille sheet display which is manufactured on a plastic film integrating the active matrix of organic transistors with polymer actuator array based on a perfluorinated polymer electrolyte membrane. The device is a thin, lightweight, flexile sheet Braille display. (b) Picture of the device assembly. Some parts of the device are removed intentionally to show inner structures of this device. This device is composed of three layers, an organic transistor sheet, a polymeric actuator sheet, and a cover layer. (c) Circuit diagram of the Braille sheet display. Each polymeric actuator is connected to one organic transistor. The vertical and the horizontal lines represent bit and word lines, respectively.

Fig. 2 shows the cross-sectional structure of a single Braille cell comprising one transistor and one actuator. The manufacturing process flow will be explained in the next section. When a voltage is applied to the polymeric actuators, the sheet-type actuators bend, as shown in Fig. 2. The semisphere placed on the actuator rises with the voltage supply and pushes up a rubberlike surface. An organic transistor active matrix is used to address the pop-up dots.

B. Organic Transistors

The base films for the organic transistors are made of polyimide or poly(ethylenenapthalate) with a thickness of about 100 μm. The detailed manufacturing process flow is available in [11]. The base film is coated with a 5-nm-thick chromium adhesion layer and a 50-nm-thick gold layer. Then, a polyimide precursor (Kemitite CT4112, Kyocera Chemical) is spin coated

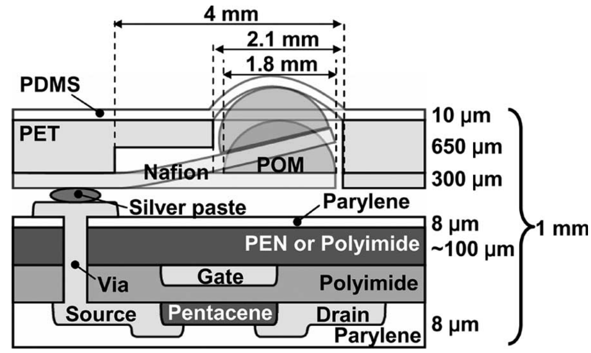

Fig. 2. Design. A cross-sectional illustration of a single Braille dot of this device. An organic transistor is connected to a polymeric actuator with silver paste patterned by a microdispenser. A semisphere is attached to the tip of each actuator.

and baked in a clean oven at 180 °C for 1 h to form a gate dielectric layer [11]. The thickness of the gate insulator is 240 nm. Next, a 50-nm-thick pentacene layer is deposited as a channel layer by using a vacuum chamber with a shadow mask. The 50-nm-thick gold is evaporated through the metal mask to form the source and drain electrodes. The organic transistor sheet is covered by an 8-μm-thick poly-chloro-para-xylylene (parylene) passivation layer. Parts of the parylene layers are removed by a CO_2 laser drilling machine to generate via holes [12].

Fig. 3 shows three images of the organic transistor sheet of different magnifications: 1) the entire chip; 2) six transistors required to display one Braille letter (six dots); and 3) one transistor. The channel length L and the width W of the transistors are 20 μm and 49 mm, respectively, which corresponds to a W/L ratio of 2450. This large W/L ratio is required to ensure a good time response of the actuators, which will be explained later. The size of the entire active matrix is 4×4 cm^2, while that of a single transistor is 1.5×1.5 mm^2.

C. Polymeric Actuators

The thin-film actuators are made of an ionic polymer metal composite (IPMC) [13]. Several soft actuators, such as dielectric elastomers [14] and conjugated polymer actuators [15], are available; however, we used IPMCs as soft actuators for the Braille displays because it is known to exhibit large displacements and high response rates.

By employing electroless plating, electrodes are formed on surfaces of a 300-μm-thick perfluoronated ion-exchange membrane, Nafion (NE-1110, DuPont) [16]. Before the plating process, both surfaces of the membrane are roughened with sandpaper in order to increase the net surface area. The membrane is immersed in a dichloro-phenanthroline-gold (III)-chloride complex ([$AuCl_2$(phen)Cl]) solution overnight at room temperature in order to impregnate the gold ion into the membrane. It is then placed in sodium sulfite solution at 60 °C for 5 h to form electrodes on both surfaces of the membrane. This plating process is repeated five or six times. The capacitance of the membrane increases with increasing repetitions of the plating process [17]. The actuator sheet is immersed in lithium chloride solution to exchange the protons

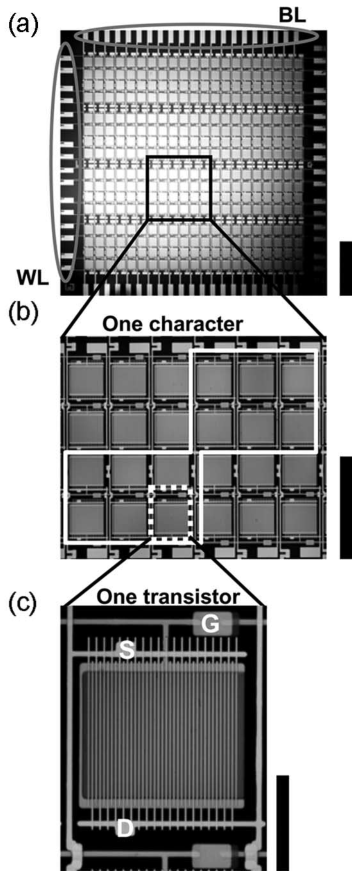

Fig. 3. Organic transistor active matrix in the chip. (a) Pictures of a whole of the organic transistor active matrix sheet, which includes 144 transistors. The scale is 1 cm. (144 dots) (b) Magnified view of transistor active matrix. The white line indicates an area of transistors for switching one character. (six dots) The scale is 5 mm. (c) A further magnified view of a single transistor. G, D, and S indicate gate, drain, and source electrode, respectively. The channel length and width are 20 μm and 49 mm, respectively. The scale is 1 mm.

inside the membrane with lithium ions. This process facilitates a large displacement, high speed, and a large generating force.

The actuator sheet is mechanically processed using a numerically controlled (NC) cutting machine to form an array of 12×12 rectangular actuators whose size is 1×4 mm^2. Note that in Fig. 4, the rectangular actuators are aligned alternately and diagonally. Due to this unique design, the present actuator array exhibits displacements, time responses, and forces of actuators that are sufficient for Braille displays; this will be explained later.

Each rectangular actuator remains connected to the parent sheet while being isolated electrically. For the isolation, insulating grooves with a depth of 80 μm are prepared on one side of the actuator sheet by using an NC drilling machine; the other side is not processed and is used as a common electrode.

We describe a supplemental experiment for the insulating groove. The groove is prepared on the surface of 1-mm-width rectangular actuators, and the resistance between the two electrodes that are separated by this groove is measured by changing the depth of the groove. As shown in Fig. 5, the two electrodes are perfectly isolated when the depth exceeds 30 μm. In this manner, all the 144 actuators on the same sheet are isolated electrically and operated separately.

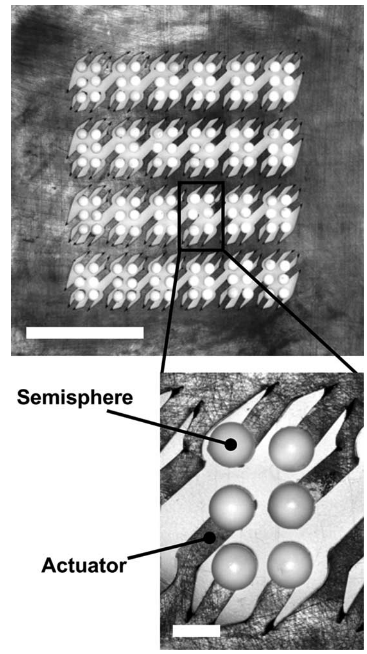

Fig. 4. Plastic actuator array. Picture of whole sheet of polymeric actuators (12×12 array) and magnified image of actuators for one letter (3×2 dots). The size of each actuator is 4 mm in length and 1 mm in width. A semisphere of radius 0.9 mm is attached to the tip of each actuator. The scales for the picture of whole sheet and magnified image are 2 cm and 2 mm, respectively.

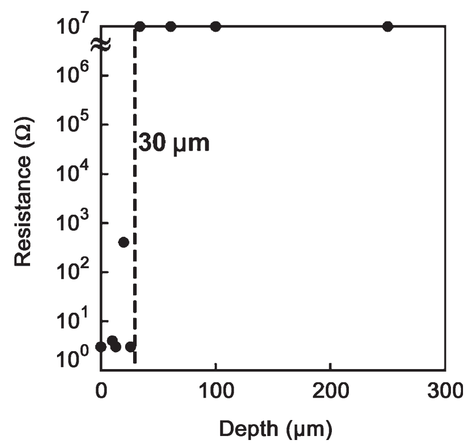

Fig. 5. Insulating grooves. Insulating property of insulating groove prepared on the actuator sheet. Two electrodes are perfectly isolated when the depth of insulating groove exceeds 30 μm.

Plastic balls with a radius of 0.9 mm are polished to be used as semispheres, which are attached by an adhesion bond on the top of the actuators. Semispheres are used instead of spheres because the former can be tightly bound to the surface of the actuator sheet. Moreover, their usage also leads to the reduction in the total thickness of the Braille displays.

D. Integration of Transistors With Actuators

The transistor and actuator sheets are laminated together after their fabrication. In order to realize via interconnections between the electrode pads of the transistors and the surface electrodes of the actuators, anisotropic conductive tapes or silver pastes patterned by a microdispenser are used. The laminated sheets are covered by a plastic frame made of 650-μm-thick poly(ethylenentereapthalate) whose surface is coated by a 10-μm-thick polydimethylsiloxane (PDMS) film. The PDMS layer is fluorinated by drop casting (Kanto Kasei Ltd., HANARL RX-410) to obtain a smooth surface.

III. Device Characteristics

In this section, we report the characteristics of discrete transistors and discrete actuators prior to integration. Then, we characterize the Braille cells that comprise transistors, actuators, and the rubberlike surface.

A. Organic Transistors

All electric measurements were performed in air by using a semiconductor parameter analyzer (Agilent 4156 C). The typical I–V characteristics are shown in Fig. 6(a) and (b). The mobility in the saturation regime is 1 $\text{cm}^2/\text{V}\cdot\text{s}$, and the ON/OFF ratio is 10^6 when the OFF current is defined as the minimum current with a positive voltage bias. In order to reduce the operation voltage to 10 V, the thickness of the gate dielectric layer is set to a value as small as 240 nm. A large current ($\sim$600 μA) is obtained at low voltages ($V_{\text{GS}} = V_{\text{DS}} = -10$ V) for the organic transistors.

As will be explained later in detail, IPMC-based actuators are usually operated in wet conditions. We have monitored the changes in the electric characteristics of organic transistors floated in purified water. We have measured a test device, which has different structural sizes, manufactured by the aforementioned process. For this device, the thickness of gate dielectric layer is 580 nm and the channel width W and length L of the transistor are 1 mm and 100 μm, respectively. As shown in Fig. 6(c), the transistors continue to exhibit a large ON current and small OFF current (ON/OFF $= 10^4$) after a period of three weeks.

B. Polymeric Actuators

One of the actuators (1×4 mm^2) is characterized before its integration with the organic transistors. The rectangular voltage of ± 3 V is applied to the actuator at a repetition rate of 2 Hz. The time response of the actuators is measured. Fig. 7(a) and (b) shows the voltage between the two actuator electrodes and the displacement of the actuators, respectively, as a function of time.

The displacement and the generating force of the actuators are measured as a function of voltage for three actuators with identical sizes of 1×4 mm^2 and plotted in Fig. 7(c) and (d), respectively. The force was measured using a load cell. The displacement and the generating force increase with the applied voltage and peak at 0.4 mm and 1.5 gf, respectively, at 2.5 V. Although the performance of the actuators depends on their structural parameters such as width, length, and thickness, the present design using actuators with a size of 1×4 mm^2 exhibits a good performance that is suitable for application in Braille sheet displays.

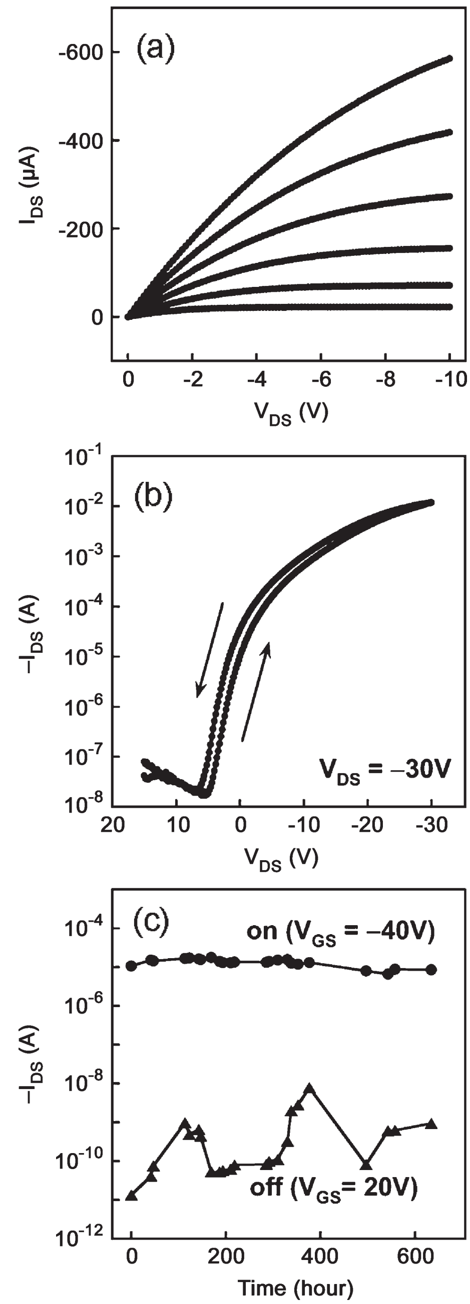

Fig. 6. Stand-alone organic transistors. (a) V_{DS}–I_{DS} characteristics of the organic transistors measured by gate voltage bias V_{GS} from 0 to -10 V with a step of -2 V. (b) V_{GS}–I_{DS} characteristic measured by $V_{\text{DS}} = -30$ V and gate voltage bias V_{GS} from 15 to -30 V. W and L are 49 mm and 20 μm, respectively. The ON/OFF ratio exceeds 10^6 when the OFF current is defined as the minimum current at positive voltage bias. (c) Degradation of transistor characteristics in wet condition. For this device, the thickness of gate dielectric layer is 580 nm, and the channel width W and length L of the transistor are 1 mm and 100 μm, respectively. The ON current at $V_{\text{GS}} = V_{\text{DS}} = -40$ V and minimum current at positive gate voltage bias of the organic transistor with parylene passivation layer immersed in deionized water are measured. The device exhibits no significant degradation over three weeks.

C. Braille Cells

In this section, one of the completed Braille cells is characterized. The time response of the actuators is measured at different gate voltages—$V_{\text{GS}} = 0, -10, -20,$ and -30 V. The power supply voltage (V_{DD}) is -10 V for the up states and 10 V for the down states. Fig. 8(a) and (b) shows the

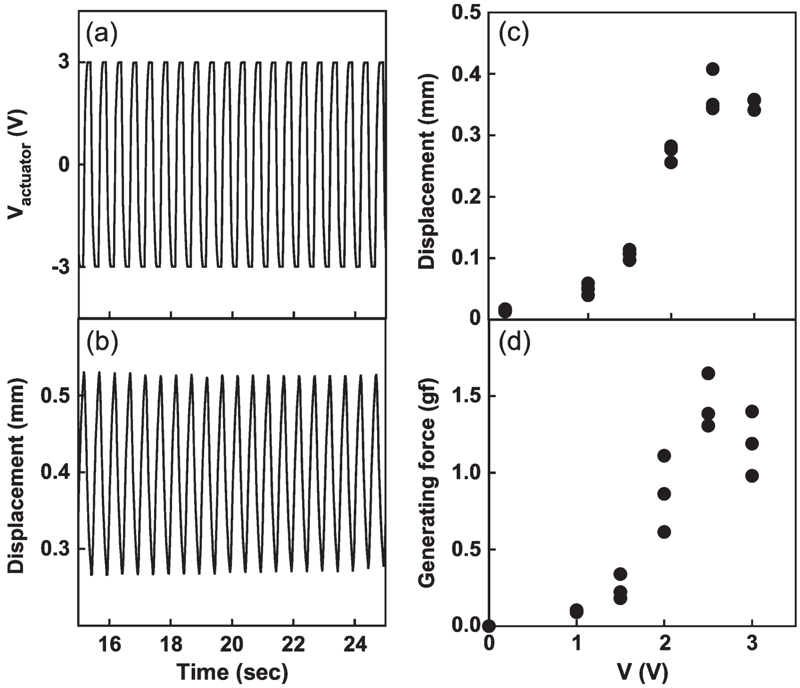

Fig. 7. Stand-alone plastic sheet actuators. A stand-alone polymeric actuator of 4 mm in length and 1 mm in width is measured. When a series of rectangular voltage of ± 3 V is input, the frequency response of the actuators extends up to 2 Hz. The voltage between two electrodes of actuator and displacement of actuator is shown in (a) and (b) in the same time scale, respectively. (c) The displacement and (d) the generating force of an actuator are plotted as a function of the input voltage.

voltage between two actuator electrodes and the displacement of the actuators, respectively, as a function of time. Fig. 8(c) is the magnified view of the initial elevation of the Braille dot. The time required to obtain a displacement of 0.2 mm decreases with the increase in $V_{\rm GS}$ and reduces to 0.9 s at $V_{\rm GS} = -30$ V, thus indicating that a frame rate of 1 Hz would be feasible.

We investigate the duration for which the Braille dots can maintain their displacement or upward state. A voltage $V_{\rm DD}$ of -10 V is applied for an initial several seconds, and it is then removed to obtain a ground state. As shown in Fig. 8(d), the displacement gradually decreases when $V_{\rm DD}$ is removed. However, the decay time is of the order of several minutes, which is considerably greater than the time required for visually impaired individuals to read Braille. When a longer hold time is required, the device should be refreshed at intervals of several minutes.

Fig. 9(a) shows one of the Braille dots moving upward and downward. Four Braille letters displayed by the present device are shown in Fig. 9(b). We will describe the readability of the present device in the Discussion section.

IV. Discussion

In the present device, the response of the actuators is limited by the time required to charge and discharge the actuator electrodes, which is analogous to large capacitors. In order to obtain a faster response, it is very important to increase the magnitude of current flowing into the actuator electrodes. In Fig. 10, we plot $I_{\rm DS}$ of the transistor at $V_{\rm DS} = -10$ V and the velocity of the actuators at $V_{\rm DD} = -10$ V as functions of $V_{\rm GS}$. Here, the velocity is defined as the displacement of 0.2 mm divided by the time required to obtain a displacement of 0.2 mm. As shown in Fig. 10, the $I_{\rm DS}$ curve is traced over the velocity data points. This result indicates that the speed of this device is not limited by the high-frequency response of the transistors or actuators but by the magnitude of current flow. Therefore, a larger W/L ratio of the transistors facilitates the increase in the response time.

We briefly describe the readability of the present Braille display. Four visually impaired individuals participated in the reading tests. When the operator input “Na” and “Wa” in the Japanese Braille format, all four individuals were able to recognize the letters correctly. This result shows that the generating force and the displacement of this device are sufficient to facilitate reading by the visually impaired. Further, it demonstrates the feasibility of this new design that integrates organic transistors and polymer actuators for realizing Braille sheet displays.

However, it is known that the ability of reading Braille varies across the visually impaired and, in general, a larger displacement and a larger force help them in reading Braille more easily. In particular, the variations in the displacement and the generating force of the Braille dots must be minimized for better readability, although the present device shows fairly large performance variations, as shown in Fig. 7. These variations may be ascribed to the unevenness in the electroless plating process and/or the fluctuations in the size of the actuators that arise due to the inaccuracy of the mechanical process. These imperfections would be removed by optimizing the process conditions.

The issues that remain to be addressed are the reliability and stability of the device. The IPMC-based actuators are usually

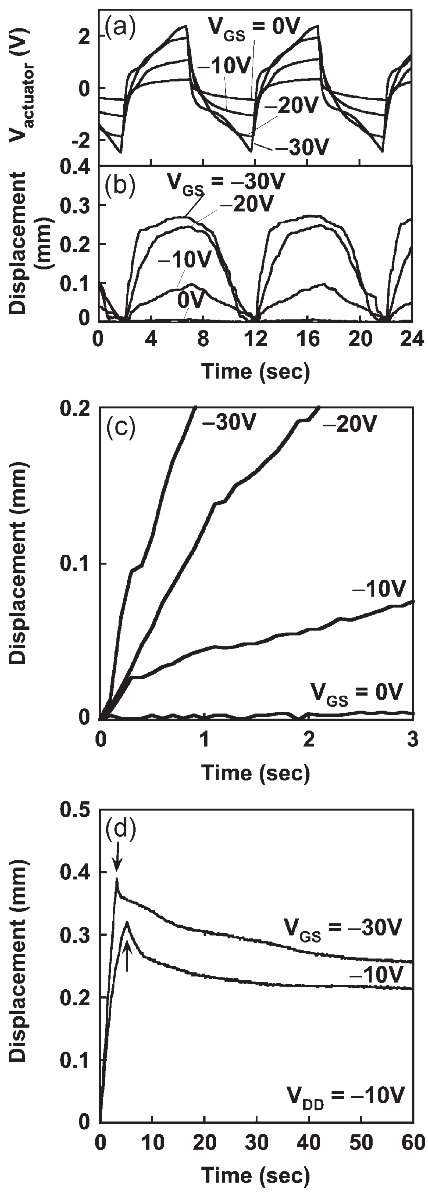

Fig. 8. Braille cells. The displacement of a Braille cell when gate voltage bias $V_{\rm GS} = 0, -10, -20,$ and -30 V is measured as a function of time. The power supply voltage $V_{\rm DD}$ is rectangular voltage of ± 10 V. The voltages between two electrodes of actuator and displacement of actuator are shown in (a) and (b), respectively. (c) Magnified view of initial rise retraced from (b). The rise time required to displace a Braille dot from 0 to 0.2 mm becomes 0.9 s at -30 V. (d) Retention property of Braille dot. A voltage $V_{\rm DD}$ of -10 V is applied for initial several seconds, and voltage is changed to ground state at the time indicated by the arrows. The displacement of actuator is plotted as a function of time.

operated in wet conditions, while organic transistors degrade easily in moisture and/or oxygen. The organic transistors with parylene passivation layers can function for more than three weeks under humid conditions, as shown in Fig. 6(c); however, a longer lifetime is required for most of their practical applications. The straightforward approach toward suppressing such degradations is to employ more sophisticated encapsulation techniques. Alternately, IPMC-based actuators can operate in ambient air when their membranes are filled with an ionic liquid [18]. Another option involves the use of carbon nanotube actuators that are soft, yet functional in air [19].

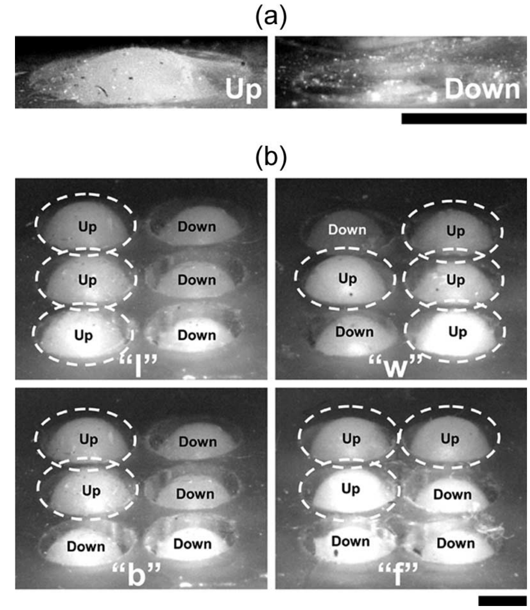

Fig. 9. Display operation. (a) Magnified pictures of one Braille dot moving upward and downward. The scale is 1 mm. (b) Pictures of Braille sheet display showing the characters "l," "w," "b," and "f" in the American Braille style.

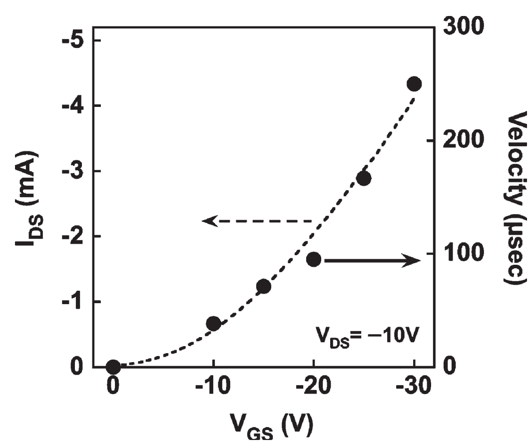

Fig. 10. Relationship between displacement of actuator and current. Two experimental results are plotted; the one is $I_{\rm DS}$–$V_{\rm GS}$ transistor characteristic ($V_{\rm DS} = -10$ V) and the other is the effective velocity of the dot as a function of $V_{\rm GS}$ ($V_{\rm DD} = -10$ V). The velocity of the dot is limited by the magnitude of the current.

Commercial Braille displays that utilize piezoelectric or solenoid actuators are available. Such actuators can control displacement with a high accuracy and also obtain large forces; however, their miniaturization is complicated. Recently, conductive polymer actuators [20] and dielectric elastomer actuators [21] have been proposed as actuators for Braille displays. However, the displacement of conductive polymer actuators was not sufficiently large, and the driving voltage of the elastomer actuators was high (> 100 V).

V. Conclusion

A lightweight, thin, and flexible sheet-type Braille display has been fabricated on a plastic film by integrating high-quality organic FETs and IPMC-based polymer actuators. The effective display size is 4×4 cm^2 and 24 Braille letters, 6 letters × 4 lines, can be displayed. The total thickness and weight of the entire device are 1 mm and 5.3 g, respectively. The new design in this paper offers an attractive scheme for reducing the thickness and weight of Braille displays and yet maintains a reasonable performance. The sheet-type Braille displays can be easily carried in pockets; therefore, they are suitable for mobile applications such as Braille e-books. It is also expected that the sheet-type Braille can be easily implemented in many digital and information appliances including cell phones without necessitating major changes in the design of the parent appliances. Thus, Braille would be more conveniently used by the visually impaired in various situations.

ACKNOWLEDGMENT

The authors would like to thank Y. Noguchi, K. Hizu, X. Wang, K. Takenoshita, Y. Takamatsu, S. Nakano, and K. Fukuda for their assistance of manufacturing process of organic transistors, K. Nakamura and Dr. T. Yamaue for fruitful discussions on soft actuators. The authors would also like to thank Prof. Y. Nakano and the members of Barrier-free Project at University of Tokyo for their cooperation to conduct the reading test and valuable advice.

REFERENCES

[1] J. A. Rogers, Z. Bao, K. Baldwin, A. Dodabalapur, B. Crone, V. R. Raju, V. Kuck, H. Katz, K. Amundson, J. Ewing, and P. Drzaic, "Paper-like electronic displays: Large-area rubberstamped plastic sheets of electronics and microencapsulated electrophoretic inks," *Proc. Nat. Acad. Sci.*, vol. 98, no. 9, pp. 4835–4840, Apr. 2001.

[2] H. Edzer, A. Huitema, G. H. Gelinck, J. B. P. H. van der Putten, K. E. Kuijk, C. M. Hart, E. Cantatore, and D. M. de Leeuw, "Active-matrix displays driven by solution-processed polymeric transistors," *Adv. Mater.*, vol. 14, no. 17, pp. 1201–1204, Sep. 2002.

[3] P. F. Baude, D. A. Ender, M. A. Haase, T. W. Kelley, D. V. Muyres, and S. D. Theiss, "Pentacene-based radio-frequency identification circuitry," *Appl. Phys. Lett.*, vol. 82, no. 22, pp. 3964–3966, Jun. 2003.

[4] R. Rotzoll, S. Mohapatra, V. Olario, R. Wens, M. Grigas, O. Shchekin, K. Dimmler, and A. Dodabalapur, "13.56 MHz organic transistor based rectifier circuits for RFID tags," presented at the Material Research Society Spring Meeting, San Francisco, CA, 2005, session I 11.6.

[5] A. C. Arias, S. E. Ready, R. Lujan, W. S. Wong, K. E. Paul, A. Salleo, M. L. Chabinyc, R. Apte, R. A. Street, Y. Wu, P. Liu, and B. Ong, "All jet-printed polymer thin-film transistor active-matrix backplanes," *Appl. Phys. Lett.*, vol. 85, no. 15, pp. 3304–3306, Oct. 2004.

[6] H. Sirringhaus, T. Kawase, R. H. Friend, T. Shimoda, M. Inbasekaran, W. Wu, and E. P. Woo, "High-resolution inkjet printing of all-polymer transistor circuits," *Science*, vol. 290, no. 5499, pp. 2123–2126, Dec. 2000.

[7] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, and T. Sakurai, "A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications," *Proc. Nat. Acad. Sci.*, vol. 101, no. 27, pp. 9966–9970, Jul. 2004.

[8] T. Someya, Y. Kato, T. Sekitani, S. Iba, Y. Noguchi, Y. Murase, H. Kawaguchi, and T. Sakurai, "Conformable, flexible, large-area networks of pressure and thermal sensors with organic transistor active matrixes," *Proc. Nat. Acad. Sci.*, vol. 102, no. 35, pp. 12 321–12 325, Aug. 2005.

[9] T. Someya, Y. Kato, S. Iba, H. Kawaguchi, and T. Sakurai, "Integration of organic field-effect transistors with organic photodiodes for a large-area, flexible, and lightweight sheet image scanner," *IEEE Trans. Electron Devices*, vol. 52, no. 11, pp. 2502–2511, Nov. 2005.

[10] Y. Kato, S. Iba, T. Sekitani, Y. Noguchi, K. Hizu, X. Wang, K. Takenoshita, Y. Takamatsu, S. Nakano, K. Fukuda, K. Nakamura, T. Yamaue, M. Doi, K. Asaka, H. Kawaguchi, M. Takamiya, T. Sakurai, and T. Someya, "Flexible, lightweight Braille sheet display with plastic actuators driven by an organic field-effect transistor active matrix," in *IEDM Tech. Dig.*, 2005, pp. 105–108.

[11] Y. Kato, S. Iba, R. Teramoto, T. Sekitani, T. Someya, H. Kawaguchi, and T. Sakurai, "High mobility of pentacene field-effect transistors with polyimide gate dielectric layers," *Appl. Phys. Lett.*, vol. 84, no. 19, pp. 3789–3791, May 2004.

[12] S. Iba, Y. Kato, T. Sekitani, H. Kawaguchi, T. Sakurai, and T. Someya, "Use of laser drilling in the manufacture of organic inverter circuits," *Anal. Bioanal. Chem.*, vol. 384, no. 2, pp. 374–377, Jan. 2006.

[13] M. Shahinpoor, Y. Bar-Cohen, J. O. Simpson, and J. Smith, "Ionic polymer-metal composites (IPMCs) as biomimetic sensors, actuators and artificial muscles—A review," *Smart Mater. Struct.*, vol. 7, no. 6, pp. R15–R30, Dec. 1998.

[14] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, "High-speed electrically actuated elastomers with strain greater than 100%," *Science*, vol. 287, no. 5454, pp. 836–839, Feb. 2000.

[15] S. Hara, T. Zama, W. Takashima, and K. Kaneto, "Artificial muscles based on polypyrrole actuators with large strain and stress induced electrically," *Polym. J.*, vol. 36, no. 3, pp. 151–161, Feb. 2004.

[16] N. Fujiwara, K. Asaka, Y. Nishimura, K. Oguro, and E. Torikai, "Preparation of gold-solid polymer electrolyte composites as electric stimuli-responsive materials," *Chem. Mater.*, vol. 12, no. 6, pp. 1750–1754, May 2000.

[17] K. Onishi, S. Sewa, K. Asaka, N. Fujiwara, and K. Oguro, "Morphology of electrodes and bending response of the polymer electrolyte actuator," *Electrochim. Acta*, vol. 46, no. 5, pp. 737–743, Jan. 2001.

[18] M. D. Bennett and D. J. Leo, "Ionic liquids as stable solvents for ionic polymer transducers," *Sens. Actuators A, Phys.*, vol. 115, no. 1, pp. 79–90, Sep. 2004.

[19] T. Fukushima, K. Asaka, A. Kosaka, and T. Aida, "Fully plastic actuator through layer-by-layer casting with ionic-liquid-based bucky gel," *Angew. Chem. Int. Ed.*, vol. 44, no. 16, pp. 2410–2413, Apr. 2005.

[20] G. M. Spinks, G. G. Wallace, J. Ding, D. Zhou, B. Xi, and J. Gillespie, "Ionic liquids and polypyrrole helix tubes: Bringing the electronic Braille screen closer to reality," in *Proc. SPIE Smart Struct. and Mater.: EAPAD*, 2003, pp. 372–380.

[21] S. Lee, K. Jung, J. Koo, S. Lee, H. Choi, J. Jeon, J. Nam, and H. Choi, "Braille display device using soft actuator," in *Proc. SPIE Smart Struct. and Mater.: EAPAD*, 2004, pp. 368–379.

Yusaku Kato (S'05) was born in Tokyo, Japan, in 1981. He received the M.S. degree in applied physics from the University of Tokyo, in 2006, where he is currently working toward the Ph.D. degree in applied physics.

He is currently involved in the development of the new large-area integrated devices that are composed of organic transistors and other function elements.

Mr. Kato is a student member of the Materials Research Society (MRS) and the Japanese Society of Applied Physics. He is also a member of JSPS Research Fellowships.

Tsuyoshi Sekitani was born in Yamaguchi, Japan, in 1977. He received the B.S. degree from Osaka University, Osaka, Japan, in 1999 and the Ph.D. degree in applied physics from University of Tokyo, Tokyo, Japan, in 2003.

From 1999 to 2003, he was with the Institute for Solid State Physics (ISSP), University of Tokyo, where he developed measurement techniques in magnetic fields up to 600 T and studied the solid-state physics of condensed matter, especially in high-Tc superconductors. Since 2003, he has been a Research Associate with the Quantum-Phase Electronics Center, University of Tokyo. His current object of physics research is in organic semiconductors and organic-FET devices.

Dr. Sekitani is a member of the American Physical Society (APS), the Materials Research Society (MRS), the Physical Society of Japan, and the Japanese Society of Applied Physics.

Makoto Takamiya (S'98–M'00) received the B.S., M.S., and Ph.D. degrees in electronic engineering from the University of Tokyo, Tokyo, Japan, in 1995, 1997, and 2000, respectively.

In 2000, he joined NEC Corporation, Japan, where he was engaged in the circuit design of high-speed digital LSIs and developed the field of on-chip measurement macros to solve the power integrity issues. In 2005, he joined University of Tokyo, where he is an Associate Professor of VLSI Design and Education Center. His research interests include power and signal integrity issues in LSIs, low-power RF integrated circuits, low-power digital circuits, and large-area electronics with organic transistors.

Masao Doi received the degree from the Department of Applied Physics, University of Tokyo, Tokyo, Japan, in 1970.

He developed his academic career with Tokyo Metropolitan University and Nagoya University before he moved to the current position. He has been working on the flow and deformation of soft materials such as polymers, gels, and colloids and is now interested in the coupling of deformation, diffusion, and electric current taking place in the materials.

Kinji Asaka received the Ph.D. degree in science from Kyoto University, Kyoto, Japan, in 1991.

He is currently a Group Leader with the Artificial Cell Research Group, Research Institute for Cell Engineering of National Institute of Advanced Industrial Science and Technology (AIST), Osaka, Japan. His current research interests include interfacial electrochemistry and polymer actuators.

Dr. Asaka is a member of the Society of Polymer Science, Japan, and The Society of Instrument and Control and Engineers.

Takayasu Sakurai (S'77–M'78–SM'01–F'03) received the Ph.D. degree in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1981.

In 1981, he joined Toshiba Corporation, where he designed CMOS DRAM, SRAM, RISC processors, DSPs, and SoC Solutions. He has worked extensively on interconnect delay and capacitance modeling known as Sakurai model and alpha power-law MOS model. From 1988 to 1990, he was a Visiting Researcher with University of California at Berkeley, where he conducted research in the field of VLSI CAD. Since 1996, he has been a Professor with University of Tokyo, working on low-power high-speed VLSI, memory design, interconnects, and wireless systems. He has published more than 400 technical papers including 70 invited papers and several books, and has filed more than 100 patents. He is also a consultant to U.S. startup companies.

Prof. Sakurai served as a Conference Chair for IEEE/JSAP Symposium on VLSI Circuits, and IEEE ICICDT, a Vice Chair for ACM/IEEE Asia and South Pacific DAC, and a program committee member for IEEE International Solid-State Circuits Conference, IEEE Custom Integrated Circuits Conference, ACM/IEEE Design Automation Conference, ACM/IEEE International Conference on CAD, ACM FPGA workshop, ACM/IEEE International Symposium on Low-Power Electronics and Design, ACM/IEEE International Workshop on Timing Issues, and other international conferences. He was a plenary speaker for the 2003 ISSCC. He is an elected AdCom member for the IEEE Solid-State Circuits Society and an IEEE Circuits and Systems Society Distinguished Lecturer.

Takao Someya (M'03) received the Ph.D. degree in electrical engineering from University of Tokyo, Tokyo, Japan, in 1997.

In 1997, he joined Institute of Industrial Science (IIS), University of Tokyo, as a Research Associate and was appointed to be a Lecturer with the Research Center for Advanced Science and Technology (RCAST), University of Tokyo, Tokyo, Japan, in 1998, and an Associate Professor with RCAST in 2002. From 2001 to 2003, he worked with the Nanocenter (NSEC) of Columbia University and Bell Labs-Lucent Technologies, as a Visiting Scholar. Since 2003, he has been an Associate Professor with the Department of Applied Physics and Quantum-Phase Electronics Center, University of Tokyo. His current research interests include organic transistors, flexible electronics, plastic integrated circuits, large-area sensors, and plastic actuators.

Prof. Someya is a member of the IEEE Electron Devices Society, the Materials Research Society (MRS), and the Japanese Society of Applied Physics. He serves as a subcommittee member for IEEE/IEDM and a program cochair for the Third Organic Microelectronics Workshop.